Fermi National Accelerator Laboratory

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Determination of the b-Quark Production Cross Section in $p\bar{p}$ Collisions at $\sqrt{s}$ = 630 GeV

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The DØ Collaboration *
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(June 26, 1997)

Abstract

We present a preliminary measurement of the b-quark production cross section in $p\overline{p}$ collisions at $\sqrt{s} = 630$ GeV. The analysis is based on 340 nb^{-1} of data collected with the DØ detector at the Fermilab Tevatron Collider. We determine the ratio of the b-quark production cross sections at 630 GeV to 1800 GeV and compare our results with the CDF and UA1 measurements, and with the next-to-leading order QCD predictions.

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I. INTRODUCTION

The study of b-quark production in high energy hadronic interactions offers a crucial test of the perturbative quantum chromodynamics (QCD) description of heavy quark production [1,2]. The cross section for b-quark production in $p\bar{p}$ collisions has been measured by the CDF and DØ collaborations at $\sqrt{s} = 1800$ GeV using various data samples [3–5]. The cross sections agree in shape with the next-to-leading order (NLO) QCD predictions but are generally higher than the central predictions for the central rapidity region. However, they are compatible with the theoretical upper limit obtained when the uncertainties on the b-quark mass and on the factorization and renormalization scale are taken into account.

At the end of 1995, the Tevatron was operating at a center-of-mass energy $\sqrt{s} = 630$ GeV, the energy at which the b-quark cross section was measured by the UA1 experiment [6]. These Tevatron data offer a unique opportunity to measure the b-quark production cross section at two different energies using the same apparatus and to compare their ratio with the NLO QCD predictions. From a theoretical point of view, this ratio is less sensitive to a specific choice of parameters than the individual cross sections. From the experimental point of view, most of the systematic uncertainties affecting the cross section measurements should cancel in the ratio. These results were shown for the first time at the Winter 1997 Conferences [7].

II. THE DØ DETECTOR

DØ is a large multi-purpose detector operating at the Tevatron $p\bar{p}$ Collider, located at the Fermi National Accelerator Laboratory. It features a non-magnetic inner tracking system, a compact and hermetic calorimeter and an extensive muon system. The DØ detector has been described in detail elsewhere [8] and only the features relevant for this analysis will be discussed briefly.

The central muon system consists of 3 layers of proportional drift tubes and a magnetized iron toroid located between the first two layers. The magnetic field in the iron is 1.9 T and provides a measurement of the muon momentum with a resolution parameterized by $\delta(1/p)/(1/p) = 0.18(p-2)/p \oplus 0.003p$, with p in GeV/c. The calorimeter is a uranium–liquid argon sampling detector, with a fractional electromagnetic energy resolution of $15\%/\sqrt{E}$, where E is in GeV, and a fractional hadronic energy resolution of $50\%/\sqrt{E}$. Muon identification is enhanced by measuring the minimum ionizing energy deposition in the calorimeter. The total thickness of the calorimeter plus toroid in the central region varies from 13 to 15 interaction lengths which reduces the hadronic punchthrough in the muon system to less than 0.5% of all sources of low transverse momentum muons.

III. INCLUSIVE AND BOTTOM-PRODUCED MUON CROSS SECTIONS AT 630 GEV

The data used in this analysis were collected during the 1995 run of the Fermilab Tevatron collider at $\sqrt{s} = 630$ GeV and correspond to a total integrated luminosity $\int \mathcal{L} dt = 342 \pm 41$ nb^{-1}.

The study of b-quark production is based on events containing at least one muon, coming either from the direct b-quark semileptonic decay, $b \rightarrow \mu$, or the sequential decay, $b \rightarrow c \rightarrow \mu$. The events are recorded with a 2-level single muon trigger in the central part of the detector. Events containing a muon candidate with a pseudorapidity $\mid \eta^\mu \mid < 0.8$ and a transverse momentum $4 < p_T^\mu < 10$ GeV/c were retained for further analysis. To remove zones of the DØ detector with lower muon chamber efficiency, the muon azimuthal angle was required to fall between 50° and 130°, corresponding to the top part of the detector. Various muon quality cuts were applied to remove poorly measured tracks and combinatoric backgrounds. In addition, valid muon candidates were also requested to be identified as a minimum ionizing particle in the calorimeter, with a total energy deposition of at least 1 GeV and some significant energy deposition in each of the 4 hadronic layers.

The muon scintillators were used to reduce and to estimate the contamination from cosmic ray muons. For muon tracks from the $p\overline{p}$ collisions, the absolute difference between the measured and the expected time of flight, $\Delta T_{\rm tof}$, must be less than 12 ns. The cosmic ray background remaining in the final sample was determined by fitting a Gaussian plus a constant term to the $\Delta T_{\rm tof}$ distribution. The fraction of cosmic rays, f_{bgd}, exhibits a strong p_T^μ dependence: f_{bgd} is less than 5% for $p_T^\mu < 5$ GeV/c but becomes larger than 80% when $p_T^\mu > 10$ GeV/c.

The inclusive muon cross section was obtained by the relation:

$$\frac{d\sigma^\mu}{dp_T^\mu} = \frac{N_\mu \cdot (1 - f_{bgd})}{\int \mathcal{L}dt \cdot \epsilon_\mu} \cdot f_{\rm unfold} \ , \tag{1}$$

where N_μ is the number of selected muons, $\int \mathcal{L}dt$ is the integrated luminosity, ϵ_μ is the global muon detection efficiency, and $f_{\rm unfold}$ is a correction factor that accounts for the smearing due to the muon momentum resolution. The muon detection efficiency was obtained with events generated with ISAJET Monte Carlo [9], simulated with GEANT and reconstructed in the same way as the data. This efficiency is approximately 10% with some p_T^μ dependence and was cross-checked whenever possible against the data. The unsmearing of the muon transverse momentum spectrum was performed with an analytical method, fitting to the uncorrected cross section a function obtained by the convolution of a physical distribution and the muon resolution function. The correction factors $f_{\rm unfold}$ were then obtained as the ratio of the physical to the fitted function estimated at the average value of $1/p_T^\mu$ in each bin.

The muon cross section for inclusive b-quark decays was extracted as follows:

$$\frac{d\sigma_b^\mu}{dp_T^\mu} = \left(\frac{d\sigma^\mu}{dp_T^\mu} - \frac{d\sigma_{\pi/K}^\mu}{dp_T^\mu} \right) \cdot f_b \ , \tag{2}$$

where $\frac{d\sigma_{\pi/K}^\mu}{dp_T^\mu}$ represents the differential cross section for pions and kaons decaying in flight into muons, and f_b is the fraction of muons from b-quark decays in the sample after subtraction of the π/K decays. The contribution from π/K decays to the differential muon cross section was estimated from ISAJET. The CDF study of inclusive particle production at $\sqrt{s} = 1.8$ TeV has shown that the ISAJET prediction for charged-hadron p_T distribution was in good agreement with the data [10]. The f_b fraction was also calculated with ISAJET: it is of the order of 63% for $4 < p_T^\mu < 5$ GeV/c and becomes larger than 80% when $p_T^\mu > 8$ GeV/c.

This procedure based on ISAJET to extract the contribution from b quarks to the inclusive muon cross section was already used at 1.8 TeV [3] and was cross-checked with the data using the p_T^{rel} technique, p_T^{rel} being the transverse momentum of the muon with respect to the associated jet axis. Jets were reconstructed for $E_T^{jet} > 8$ GeV, using a cone algorithm with radius $R = 0.7$, where $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. The p_T^{rel} distributions for b-quark, c-quark and π/K decays were modeled with ISAJET and fitted to the data in bins of p_T^{μ}. The fraction of muons from b quark decays measured from the data was consistent within errors with the result of ISAJET Monte Carlo simulation. The application of the p_T^{rel} technique to the 630 GeV data is under study. However, the number of muons with a jet nearby ($E_T^{jet} > 8$ GeV) represents only about 15% of the single muon sample.

The systematic errors on the inclusive muon cross section are between 16 and 22%. As shown in Table I, the main contribution to these errors comes from the uncertainty on the integrated luminosity. The systematic error on the b-produced muon cross section ranges between 28 and 53% because of the π/K subtraction procedure. The muon cross section corresponding to inclusive b-quark decays is shown in Fig. 1. The theoretical spectrum was obtained with the HVQJET Monte Carlo event generator [11], using the MRSA' parton distribution function [12], together with the parameters $\Lambda^{(5)}_{\overline{MS}} = 152$ MeV, a b-quark mass $m_b = 4.75$ GeV$/c^2$, a renormalization and factorization scale $\mu = \mu_0 \equiv \sqrt{m_b^2 + (p_T^b)^2}$, and $Br(b \to \mu) = 0.105$. The theoretical uncertainties were obtained by varying m_b between 4.5 and 5 GeV$/c^2$, and μ between $\mu_0/2$ and $2\mu_0$.

TABLE I. Relative systematic errors on the inclusive muon cross section ($\Delta\sigma^{\mu}$), the b-produced muon cross section ($\Delta\sigma_b^{\mu}$), and the b-quark cross section ($\Delta\sigma^b$) (in %). The contribution of each factor to these systematic errors is also shown.

p_T^{μ} (GeV/c)	Δf_{bgd}	$\Delta\epsilon_{\mu}$	$\Delta\mathcal{L}$	Δf_{unfold}	$\Delta\sigma^{\mu}$	$\Delta\sigma_{\pi/K}$	Δf_b	$\Delta\sigma_b^{\mu}$	$\Delta(\sigma_b/\sigma_{\mu})$	$\Delta\sigma^b$
4 – 5	0.4	9.6	12	4.1	15.9	49.7	10.5	53.2	10.6	54.2
5 – 6	1.3	8.4	12	5.8	15.8	34.9	12.3	40.2	12.4	42.1
6 – 8	3.0	8.0	12	8.0	16.8	19.0	12.3	28.2	13.5	31.3
8 – 10	10.4	9.4	12	11.6	21.8	19.0	8.3	30.1	13.8	33.1

IV. BOTTOM-QUARK CROSS SECTION AT 630 GEV

To extract an inclusive b-quark production cross section from the muon spectrum, the method developed by UA1 and used by CDF and DØ at $\sqrt{s} = 1.8$ TeV was applied. The relation between the b-quark cross section and the experimental muon spectrum is given by

$$\sigma^b(p_T^b > p_T^{\min}) = \frac{1}{2}\,\sigma_b^{\mu}(p_T^{\mu 1}, p_T^{\mu 2})\,\frac{\sigma_{MC}^b}{\sigma_{MC}^{\mu}}\ , \tag{3}$$

where $\sigma_b^{\mu}(p_T^{\mu 1}, p_T^{\mu 2})$ is the b-produced muon cross section integrated over the interval $p_T^{\mu 1} < p_T^{\mu} < p_T^{\mu 2}$, σ_{MC}^b is the total inclusive b-quark cross section for $p_T^b > p_T^{\min}$ and rapidity $|\, y^b \,| < 1$,

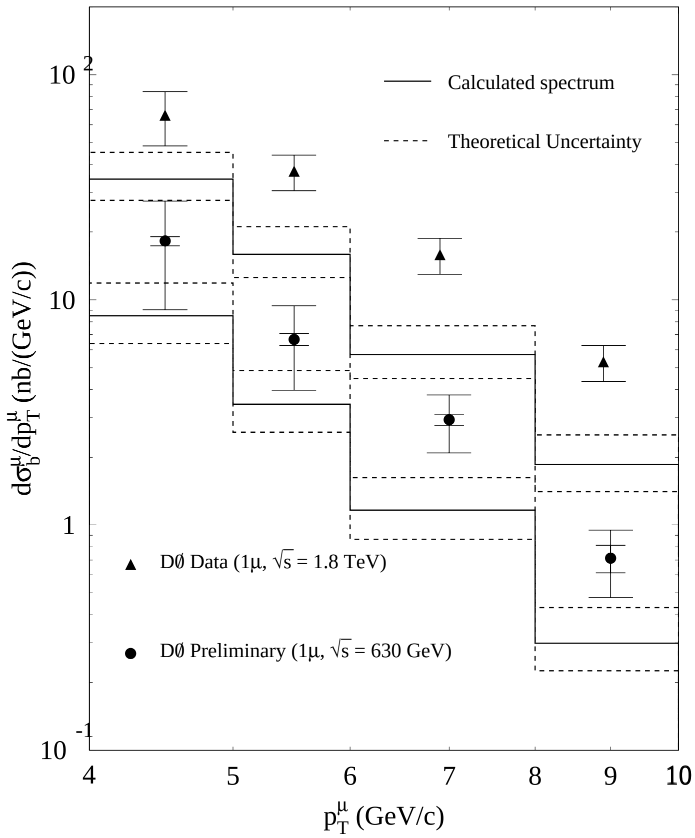

FIG. 1. The b-produced muon cross sections measured by DØ at 630 GeV (closed circles) and 1800 GeV (triangles), compared with the HVQJET predictions (see text). For the low energy results, the inner and outer bars correspond to the statistical and total errors, respectively.

and σ^μ_{MC} is the cross section for production of b quarks that decay to muons within the p_T^μ interval and with $p_T^b > p_T^{\min}$. The factor $\frac{1}{2}$ yields the cross section average for b and $\bar{b}$ production from the measurement of μ^+ and μ^- data.

The $\sigma^b_{MC}/\sigma^\mu_{MC}$ conversion factors were evaluated with HVQJET, using the MRSA' parton distribution function together with the parameters $\Lambda^{(5)}_{\overline{MS}} = 152$ MeV, $m_b = 4.75$ GeV$/c^2$, $\mu = \mu_0$, and $Br(b \rightarrow \mu) = 0.105$. Table I summarizes the systematic uncertainties affecting the derived b-quark cross section.

The b-quark production cross section obtained by the DØ experiment is shown in Fig. 2a, together with the CDF [13] and UA1 results [6]. The CDF and DØ cross sections, measured for $| y^b | < 1$, were scaled by a factor obtained with MNR [2] to correspond to the same rapidity interval as UA1, $| y^b | < 1.5$. The NLO QCD prediction, shown by the solid line, is based on the MNR calculation using the MRSA' structure function with $\Lambda^{(5)}_{\overline{MS}} = 152$ MeV, $m_b = 4.75$ GeV$/c^2$ and $\mu = \mu_0$. The dashed curves show the theoretical uncertainties obtained by varying m_b between 4.5 and 5 GeV$/c^2$, and μ between $\mu_0/2$ and $2\mu_0$. The ratio of the measured cross sections to the theoretical expectations is shown in Fig. 2b. The weighted average of these ratios is equal to 2.1 ± 0.2.

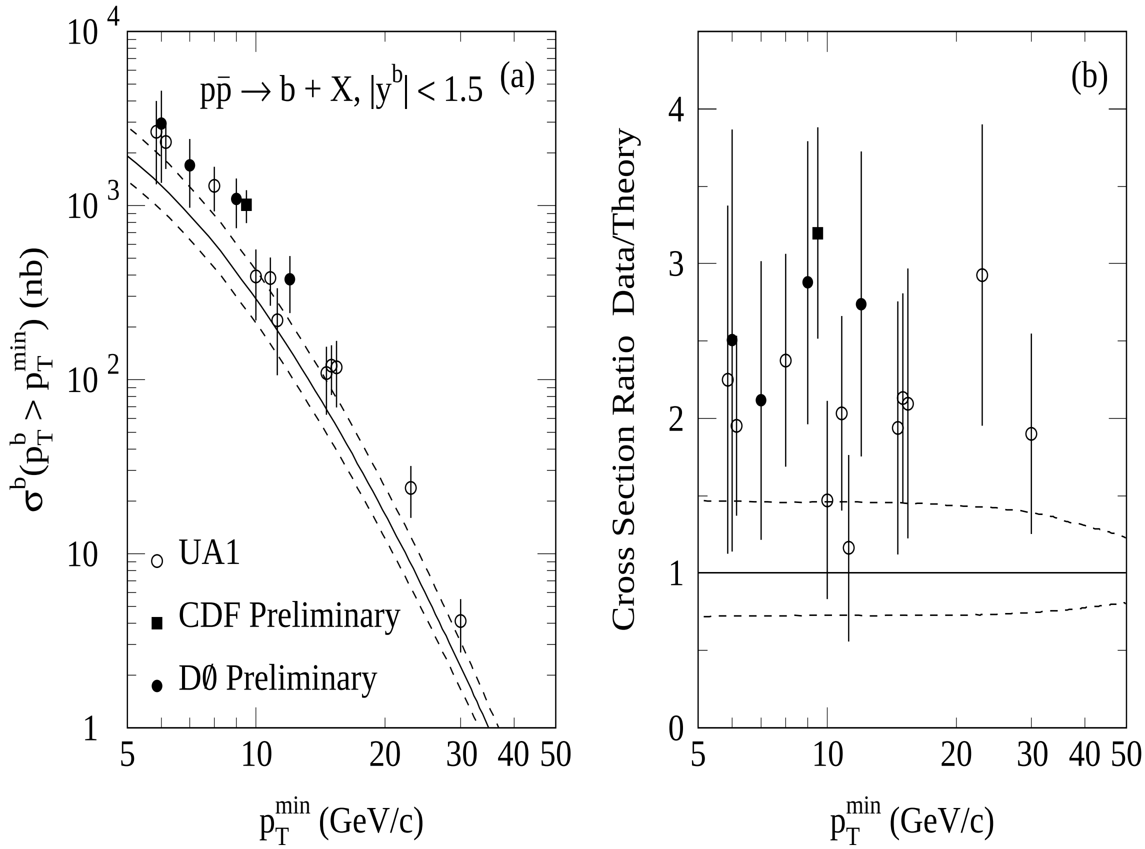

FIG. 2. The b-quark production cross sections measured by CDF (square), DØ (closed circles) and UA1 (open circles) at 630 GeV compared with the NLO QCD predictions (see text).

V. ENERGY DEPENDENCE OF THE BOTTOM-QUARK CROSS SECTION

To study the energy dependence of the b-quark production cross section, we have recomputed the inclusive b-quark cross section at $\sqrt{s} = 1800$ GeV starting from the b-produced muon cross section (see Fig. 1) and applying the $\sigma^b_{MC}/\sigma^\mu_{MC}$ factors obtained with HVQJET as before. The ratio of the absolute cross sections independently measured at 630 GeV and 1800 GeV was then computed, assuming that only the systematic errors on the integrated luminosity and the $\sigma^b_{MC}/\sigma^\mu_{MC}$ conversion factors were correlated between each measurement.

This ratio is presented in Fig. 3. The horizontal inner and outer bars show the statistical and the total errors, respectively. These results are in good agreement with the NLO QCD predictions, computed in the same way as in Fig. 2. The CDF result [13] is also shown in Fig. 3. This ratio was obtained by selecting two identical event samples at 630 and 1800 GeV and correcting for the different acceptance for b events at the two energies. Both the DØ and CDF measurements are in good agreement with the theoretical expectation.

Future analyses of the 1993-1994 DØ data using the same methods as for the low energy data should allow a significant reduction of the errors on the $\sigma^b(630 \text{ GeV})/\sigma^b(1800 \text{ GeV})$ ratio.

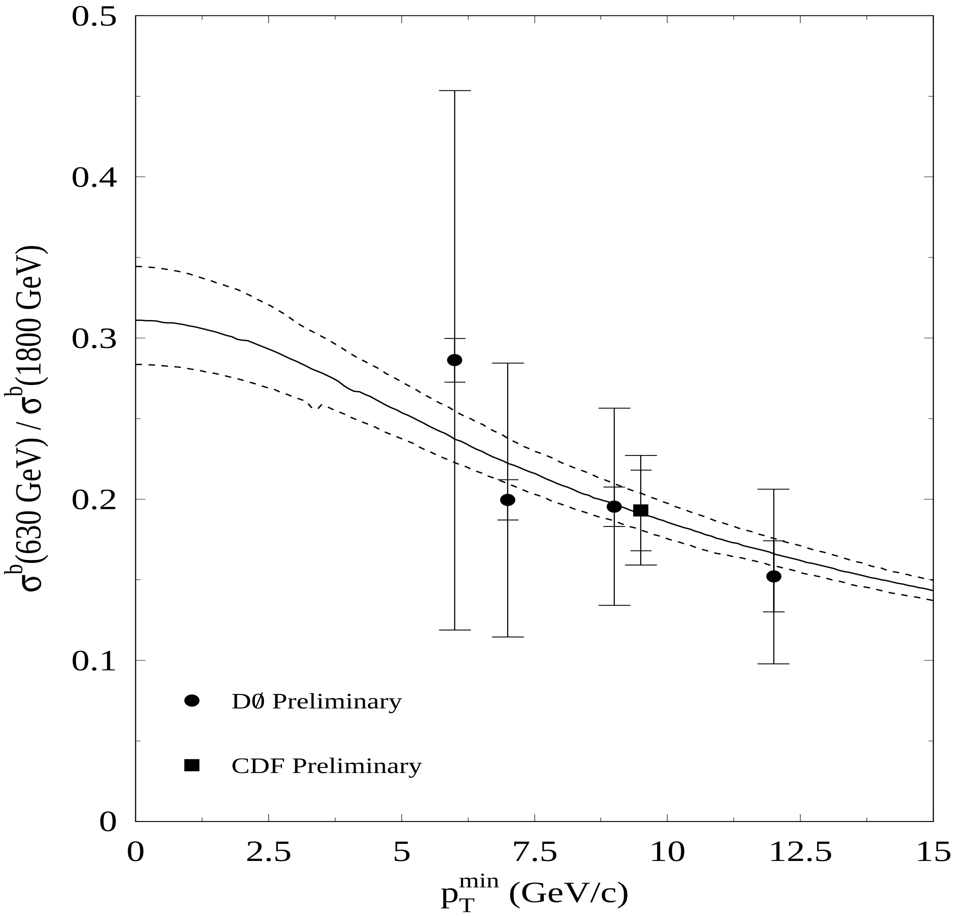

FIG. 3. Ratio of b-quark production cross sections at 630 GeV to 1800 GeV. The full curve shows the theoretical expectation while the dashed curves correspond to the theoretical uncertainties.

VI. CONCLUSION

We have presented a preliminary measurement of the b-quark production cross section in $p\overline{p}$ collisions at $\sqrt{s} = 630$ GeV, based on 340 nb^{-1} of data collected by the DØ experiment at the Fermilab Tevatron collider. Our results are compatible with the CDF and UA1 measurements and agree in shape with the NLO QCD predictions, but the combined weighted average of the ratio Data/Theory is equal to 2.1 ± 0.2. However, the ratio of cross sections at 630 and 1800 GeV is compatible with the NLO QCD expectation.

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